Step and flash imprint lithography for manufacturing patterned media

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The ever-growing demand for hard drives with greater storage density has motivated a technology shift from continuous magnetic media to patterned media hard disks, which are expected to be implemented in future generations of hard disk drives to provide data storage at densities exceeding 10^{12} bits/in.^{2}. Step and flash imprint lithography (S-FIL) technology has been employed to pattern the hard disk substrates. This article discusses the infrastructure required to enable S-FIL in high-volume manufacturing, namely, fabrication of master templates, template replication, high-volume imprinting with precisely controlled residual layers, and dual-sided imprinting. Imprinting of disks is demonstrated with substrate throughput currently as high as 180 disks/h (dual sided). These processes are applied to patterning hard disk substrates with both discrete tracks and bit-patterned designs. © *2009 American Vacuum Society.* [DOI: 10.1116/1.3081981]

I. INTRODUCTION

The history of magnetic recording dates back over a century,[1] and is driven by the interactions between an external field and a magnetic material. Magnetic recording technology was practically applied to the fabrication of hard disk drives in 1956, and increases in data storage density have spanned eight orders of magnitude in the past 50 years.[2,3] As a result of these tremendous advances, the placement of hard drives is ubiquitous: routine applications include servers, desktop computers, laptops, digital video recorders, game consoles, video cameras, and so on.

This remarkable progress has been enabled by advances in the coating of thin magnetic films having characteristic grain sizes as small as 7 nm. The individual grains, typically made of a material such as CoCrPt for perpendicular recording,[4] are separated from one another by an oxide that forms at the grain boundaries. A cluster of grains with similar magnetization make up a single bit of stored data; many adjacent grains are required to form a volume that is large enough to be precisely "written" and "read" by the head element of a disk drive. In recent years, improvements in bit storage density have been driven by the development of deposition techniques that are capable of producing films with smaller magnetic grains. However, the superparamagnetic effect will eventually limit this progression. Smaller grains eventually become magnetically unstable and the likelihood of a grain spontaneously flipping increases—ultimately resulting in the loss of stored data.

The practical limitations of the superparamagnetic effect can be avoided by patterning the boundaries between the magnetic domains, hence the term "patterned media."[5,6] Patterning the magnetic material creates magnetic switching volumes with highly uniform size and shape, which can greatly facilitate the reading and writing of bits. Because the magnetic switching volume is defined lithographically—and not by the random grain structure of the deposited film—it is possible to robustly address the magnetization of a single magnetic grain. The introduction of patterned media technology into manufacturing is expected to enable the next generation of hard disk drives with a storage density exceeding 10^{12} bits/in.^{2} (1 Tbit/in.^{2}). Realization of this technology transition will require industrial-scale lithography at unprecedented levels of feature resolution, pattern precision, and cost efficiency.

Two primary alternatives to patterned media have been proposed to overcome the limits associated with superparamagnetism. In the simplest example, lithography and etch processes are employed to isolate each bit of data in a precise island of magnetic material. Each bit is patterned individually, so this approach is termed "bit-patterned media" (BPM). BPM patterns typically comprise dense pillars in a close-packed array, which represents a best-case scenario for data storage density [Fig. 1(a)]. Unfortunately, the BPM approach is simple only in concept: Practical implementation would require a number of rapid advances in template fabrication, etching of magnetic material, addressing of the drive head element, etc. The challenges of the BPM approach to patterned media are being addressed by an intermediate approach, in which individual tracks of data are patterned instead of individual bits. Thus, the dimensions of the magnetic domains are constrained in one dimension by patterning narrow gaps between discrete concentric tracks of magnetic material. This approach is termed "discrete track recording" (DTR) and the patterns comprise arrays of lines [Fig. 1(b)]. The processing demands of DTR are significantly

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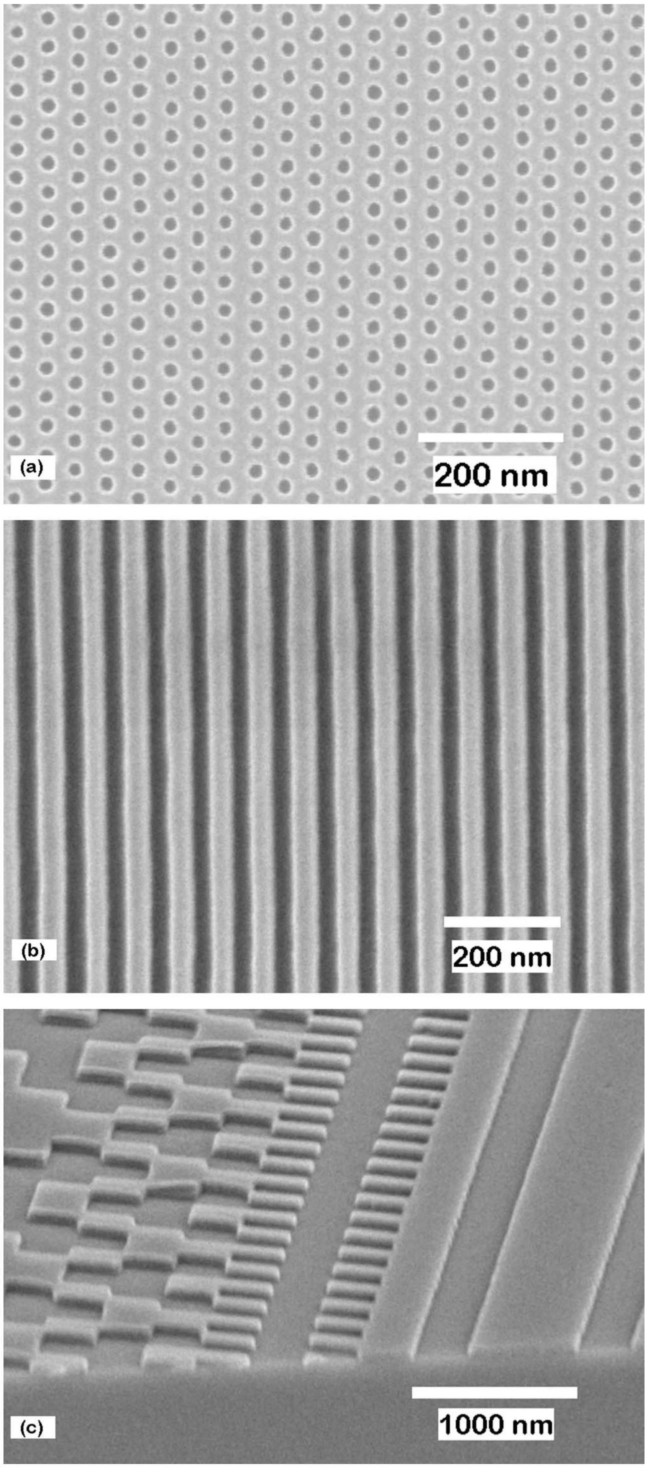

FIG. 1. SEM images of imprinted resist patterns. (a) BPM patterns at 40 nm pitch (0.4 Tbit/in.^{2}), (b) DTR track patterns at 70 nm pitch, and (c) a tilt image from a servo pattern region.

relaxed in terms of resolution and dimensional uniformity, and it is expected that the process experience gained through the implementation of DTR will be valuable toward the introduction of BPM technology.

Along with tracks or bits, additional features termed "servo patterns" are included on hard disks to enable the head element to read and write data at precise locations.[3] The design of servo patterns plays a key role in the performance of the disk drive, and these patterns are typically proprietary to each drive manufacturer. Servo patterns contain features with dimensions that are typically two times to ten times larger than the data features, and include arrays of lines, dots, and combinations thereof [Fig. 1(c)]. Servo patterns are placed at regular angular intervals around the disk, with the effect of dividing the disk surface into a large number of wedge-shaped sectors. A typical disk might be divided into 100–400 sectors, with servo patterns occupying 5%–20% of the active surface of the disk. Servo patterns are employed on conventional, "unpatterned" media by recording the patterns in the continuous media via a separate process that is very similar to the normal operation of the disk drive. Servo recording is a time-consuming serial process, and so the ability to prepattern the servo features is a significant additional benefit.

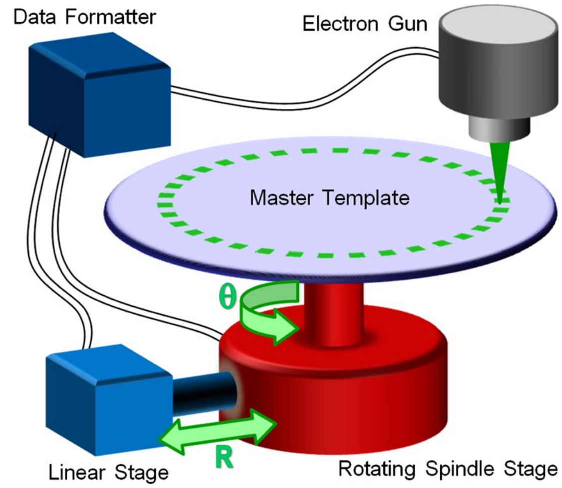

FIG. 2. (Color online) Schematic of an electron-beam patterning system with a rotating stage, for creating concentric patterns on template substrates.

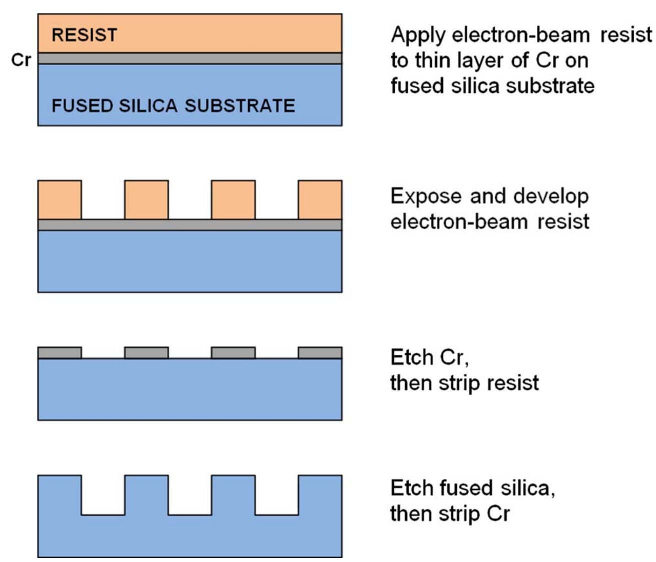

FIG. 3. (Color online) Process flow for pattern transfer by subtractive patterning of a Cr etch mask.

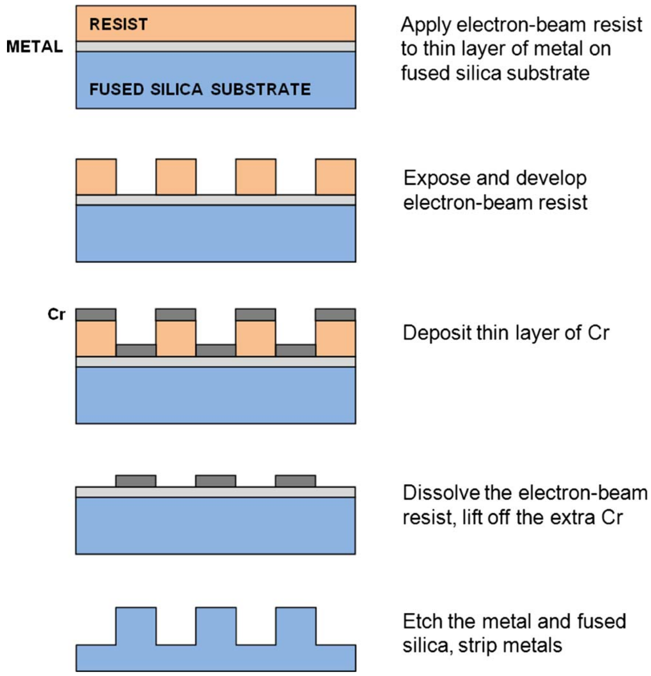

FIG. 4. (Color online) Process flow for pattern transfer by additive lift-off patterning of Cr etch mask.

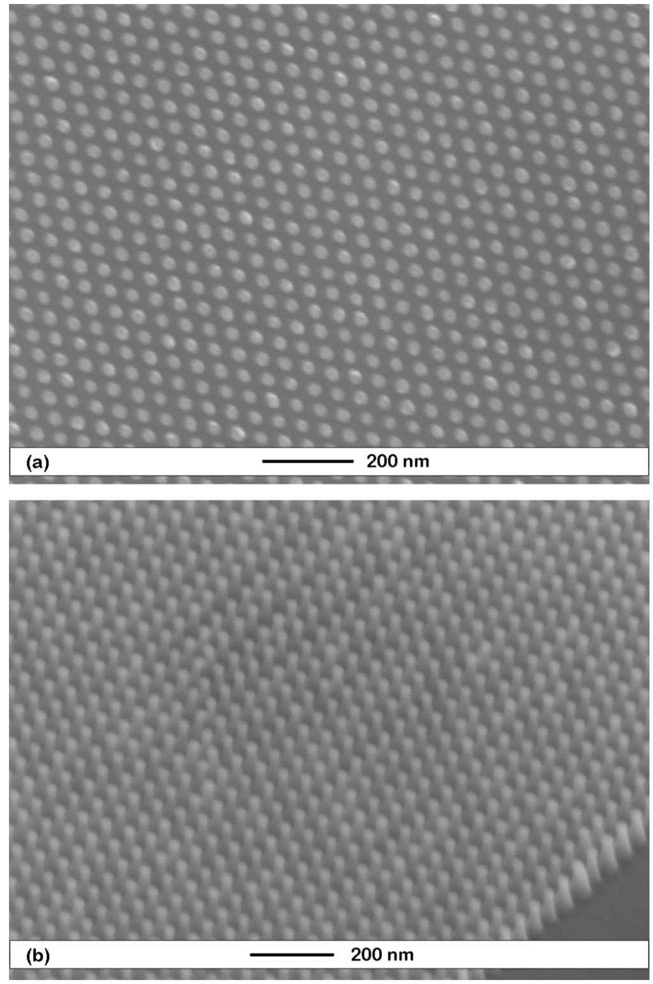

FIG. 5. Pattern transfer by lift-off: (a) Cr dots after lift-off and (b) tilt image of fused silica topography after etching.

Industrial-scale manufacturing of patterned media poses a number of lithography challenges. This article discusses the application of Step and Flash® imprint lithography (S-FIL®) technology to the patterning of DTR and BPM designs on hard disk media. In particular, we address the lithographic unit processes necessary for high-volume manufacturing of patterned magnetic media: pattern definition, master template fabrication, template replication, and dual-sided imprinting of disks.

II. MASTER TEMPLATE FABRICATION

Fabrication of a master template for patterned media applications requires an electron-beam writing system with a rotating stage. This configuration is well suited for defining the concentric layouts that are required for patterned media applications, and several suppliers now offer such systems (e.g., Crestec, Elionix, and Pioneer Electronics). Conventional electron-beam write tools have x-y stages and operate by stitching together adjacent exposure fields, but patterned media applications have very low tolerance for the stitching errors that inevitably occur at the boundaries between exposure fields.

A schematic version of a rotary-stage r-θ pattern generator is shown in Fig. 2. A template blank, which has been coated with an electron-beam resist material such as ZEP520A (Zeon Corporation), is fixed on a rotary stage that turns at speeds between 100 and 4000 rpm. The rotating stage is translated in a radial direction to enable precise recording of concentric patterns at different radial locations. The tracks or bits that form the data regions are defined by a data formatter, which also defines the servo patterns that play a key role in positioning of the head during the read/write

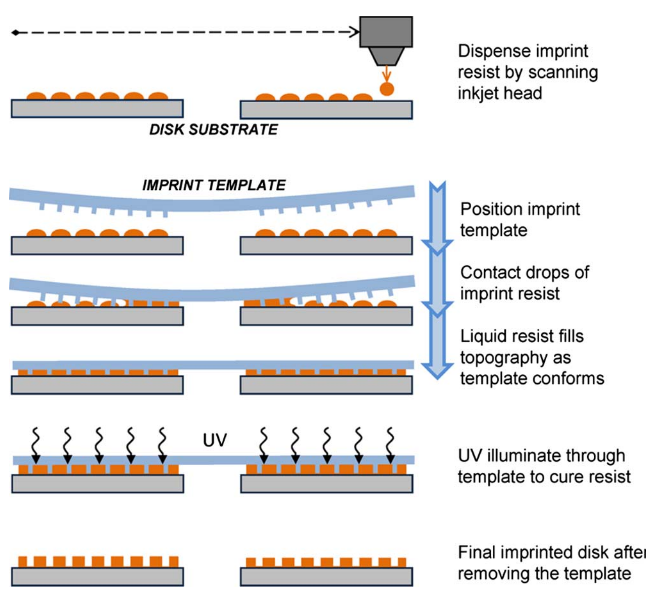

FIG. 6. (Color online) Process flow for imprint patterning of hard disk substrates.

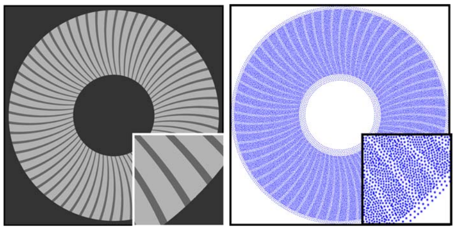

FIG. 7. (Color online) Schematic of local pattern density variations (left) and targeted drops of imprint material dispensed by inkjet head (right).

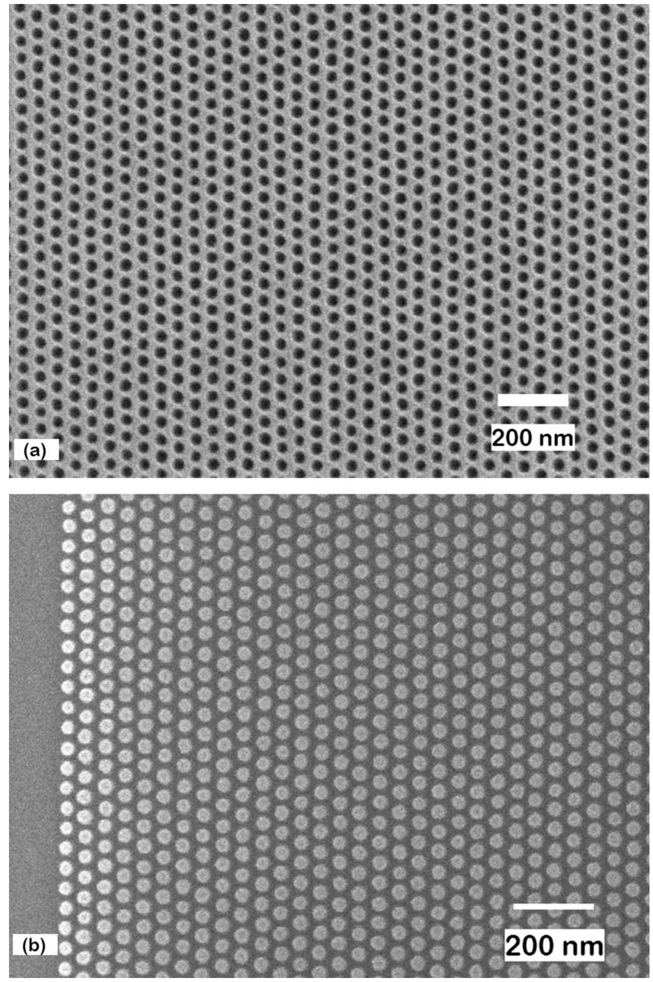

FIG. 9. Replication of a BPM template: (a) imprinted resist pattern from master template and (b) imprinted resist pattern from replicated template. Note that the imprint template tone has been inverted in the replication process.

operations. Patterning is performed by deflecting the electron beam in both radial and tangential directions to achieve concentric patterning of discontinuous structures with minimal beam blanking. Minimization of beam blanking can greatly improve the patterning speed of these tools, but exposure of a fully patterned template still requires several days of continuous writing. Precise placement of features and uniform patterning are key factors that will affect the performance of patterned media data storage, so improving the stability of the mechanical and electromagnetic systems is a key challenge for achieving data storage density above 1 Tb./in.^{2}.

After the primary step of resist patterning via electron-beam recording, a variety of pattern transfer processes can be used to produce the desired topography in the fused silica master template. Two common approaches are depicted in Figs. 3 and 4. Figure 3 shows a conventional subtractive etch process, which is very similar to the processes that are used in the photomask industry for fabrication of phase-shifting photomasks.[7] In this approach, a hard mask layer (e.g., Cr) is used to define the features in the fused silica and is stripped away in a subsequent processing step. This process produces a template in which the patterns are recessed while the field is unetched; this type of template is termed "field proud."

Alternatively, a "feature proud" surface can be fabricated with a lift-off process, as pictured in Fig. 4. The fused silica substrate is first coated with a thin (<5 nm) metal film, which serves as a charge dissipation layer during the electron-beam exposure of the resist. After the resist is patterned, a thin layer of Cr is deposited on the substrate, coating the top of the resist pattern as well as the exposed portions of the substrate. A lift-off process is employed to remove the unwanted resist as well as the Cr that coats the surface of the resist. The Cr is then used as an etch mask for plasma-based processes to pattern both the underlying conducting layer and the fused silica substrate. The remaining metal films are then stripped, leaving the patterned fused silica topography. The process has been shown to work particularly well for creating pillar-type features on templates, as shown in Fig. 5. Pictured in Fig. 5(a) is an array of 50 nm pitch Cr dots after lift-off. The final fused silica pillars on the template, formed by a plasma etch in fluorocarbon gas chemistry, are shown in Fig. 5(b). This process has been demon-

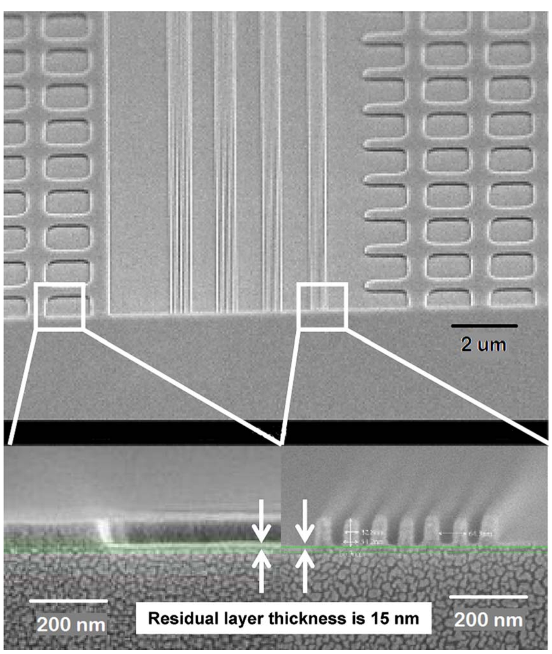

FIG. 8. (Color online) Uniform residual layers are obtained across the entire substrate, independent of pattern density and feature size variations.

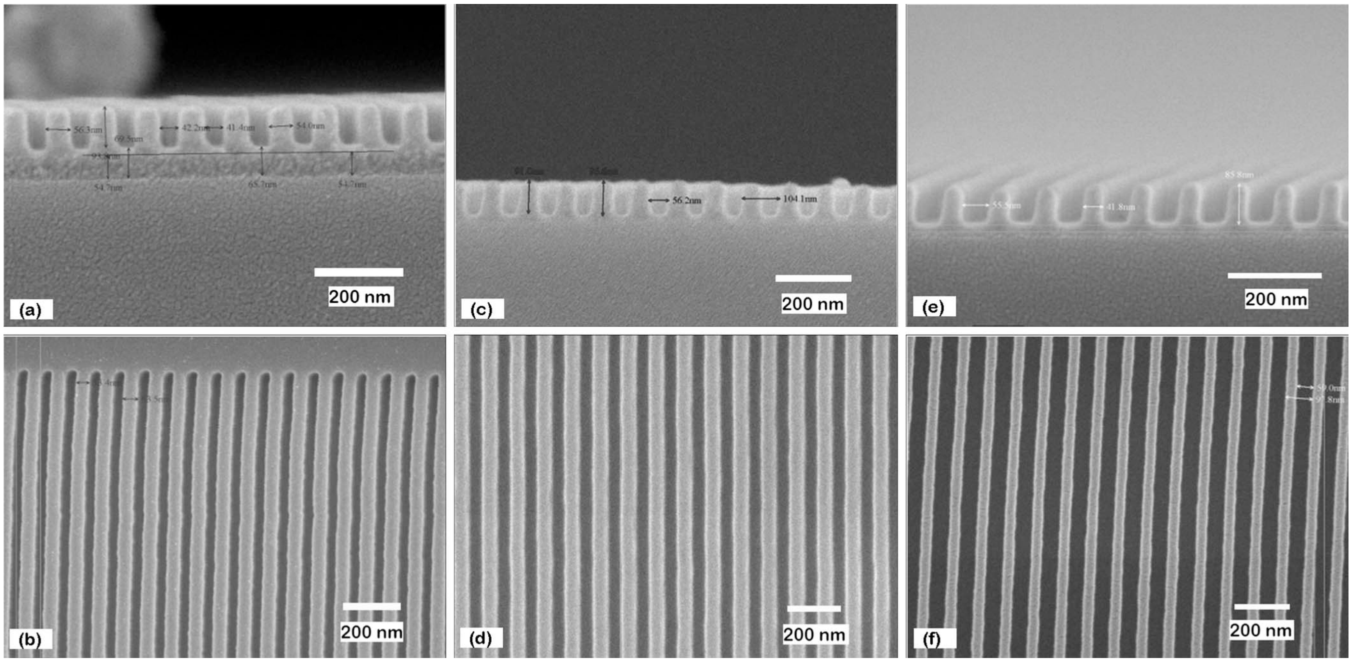

FIG. 10. Two iterations of template replication for DTR patterns: (a) cross-section of imprinted resist from master template and (b) top-down image of imprinted resist from master template. This master template was replicated to create a submaster template, which was imprinted to create the resist patterns shown in (c) and (d). This submaster template was replicated to create a working template, which was imprinted to create the resist patterns shown in (e) and (f).

strated for fabricating template pillar arrays with pitches as small as 25 nm, corresponding to an area density of 1 Tbit/in.^{2}.[8]

III. IMPRINT PROCESS

A. Details of the imprint process

For semiconductor device applications, a Drop-on-Demand™ S-FIL process has been used with a step-and-repeat imprint strategy to pattern fields on Si wafers.[9] Yoneda *et al.*[10] demonstrated an 18 nm resolution and overlay performance better than 15 nm, 3σ. With a suitable template, the same technology can be applied to the imprint pattering of an entire wafer substrate in one step, with no need for a step-and-repeat approach. As an example, Miller *et al.*[11] demonstrated imprinting of dense photonic crystal arrays across the surface of GaN-coated Al_2O_3 substrates for production of high-performance light-emitting diodes.

Patterning of a hard disk can be performed in the same way, as shown schematically in Fig. 6. First, the liquid acrylate imprint resist is deposited with a multinozzle inkjet head across the active surface of the disk substrate. The template is lowered until contact is made with the imprint resist, and capillary action induces the liquid imprint resist to completely fill the region between the substrate and the topography of the imprint template. The imprint material is then photopolymerized via ultraviolet illumination through the fused silica template (Fig. 6). The template is then separated from the disk, which now contains a relief image corresponding to the template pattern. (It should be noted that the same process that is used to pattern disk substrates can also be employed to pattern template substrates, thus providing the valuable capability to replicate the master template; this subject is addressed in Sec. III B) Following the imprint step, the resist pattern must be transferred into the underlying magnetic material to define the magnetic switching volumes. This can be accomplished by a number of processes, including ion milling and ion irradiation.[12] Depending on the pattern transfer scheme, it might be necessary to include an etching step to remove the thin residual layer that forms at the base of the imprinted resist pattern.

The inkjet-based drop-on-demand approach in dispensing imprint material provides several significant advantages over a traditional spin-coating approach. First, it is a straightforward and fast method for depositing material on surfaces of arbitrary shape, such as the annular disk-type substrates used in the hard drive industry. The process is inherently cleaner than spin-coating methods, and front- and backside edge bead removal is not required. Elimination of expensive two-sided coat and bake systems provides a compelling cost advantage. Drop-on-demand technology also allows the imprint tool to selectively place imprint resist to match the local pattern density of the template. The imprint material is dispensed as individual drops that are approximately 5 pl in volume; roughly 2×10^4 drops are dispensed to pattern a disk surface with a total volume of approximately 100 nl. The precision of the dispense technique makes it possible to compensate for localized variations in pattern density across the template, and thus maintain a highly uniform residual layer across the entire substrate surface (Fig. 7). The ability to form consistent residual layers is pictured in Fig. 8 for both nanoscale structures (such as discrete data tracks or bits) and microscopic patterns (such as servo regions). Because the imprint liquid is dispensed with picoliter-level precision to match the local volume required by the template patterns, there is no waste stream of excess resist material or rinse solvent. The drop-on-demand process achieves very high efficiency of material usage: whereas a spin-coating process requires approximately 1 ml of resist to coat both sides of a single disk, the same volume of imprint resist is sufficient for patterning approximately 5000 disks.

B. Template replication using step and flash imprint lithography

Industrial forecasts suggest that the market demand for hard disk recording media will reach 10^9 units in the next few years. Fabrication of patterned media to meet this demand will require a large supply of imprint templates: The lifetime of a single imprint template is anticipated to be approximately 10^4 imprints,[13] suggesting that at least 10^5 templates will be required. It is not feasible to employ electron-beam patterning directly to create this volume of templates. Instead, a "master" template—created by directly patterning with an electron-beam tool—will be replicated many times to produce the required supply of "working" templates for patterning disk media. Several replication schemes are being considered, including single-step replication (master template to working template) and two-step replication (master template to "submaster" template to working template).[14]

The replication of templates can be accomplished using the same imprinting process as described in Sec. III A. After imprinting, a plasma-based etch process is employed to transfer the relief pattern into the fused silica. An example of the progression from master template to working template is shown in Fig. 9 for the case of a BPM design. Figures 5(a) and 5(b) depict pattern transfer from the Cr etch mask (created by lift-off) to the final topography in a fused silica master template. The master template was then used to create a resist pattern on a template substrate [Fig. 9(a)]. The resist pattern was etch transferred into the underlying fused silica and the etch mask residues were stripped, thus creating a working template. Finally, the working template was used to form a bit pattern array on a disk [Fig. 9(b)]. In this example, the feature pitch is 50 nm, corresponding to a BPM feature density of 2.5×10^{11} bits/in.^{2} (0.25 Tbit).

Figure 10 provides an example of two successive template replication steps for a DTR pattern with a track pitch of 100 nm. Here, the progression from master template to submaster template to working template is demonstrated with cross-section and top-down SEM images of imprinted resist patterns. Note that the quality of the imprinted lines is essentially constant through the successive iterations of replication. The replication process has been extended to smaller dimensions; Fig. 11 shows examples of imprinted DTR features having a resist pitch as small as 70 nm.

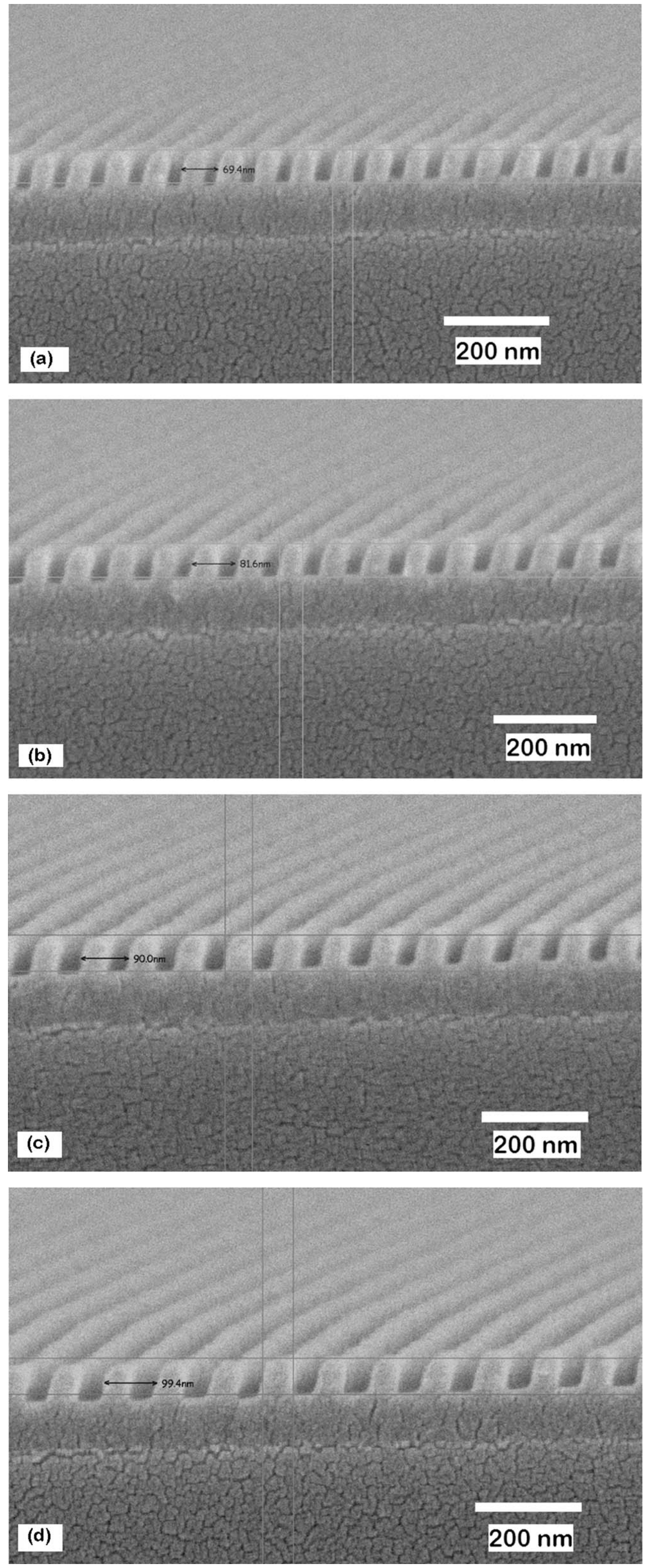

FIG. 11. Imprints from a DTR template with track pitches of (a) 70 nm, (b) 80 nm, (c) 90 nm, and (d) 100 nm.

C. Imprint tool

Two-sided imprinting of disk substrates was performed with an Imprio HD2200®—a fully automated UV-nanoimprint lithography tool that has been specifically designed for patterned media applications. The Imprio HD2200 provides the high patterning fidelity that is characteristic of UV-nanoimprint lithography,[15] with automated double-sided

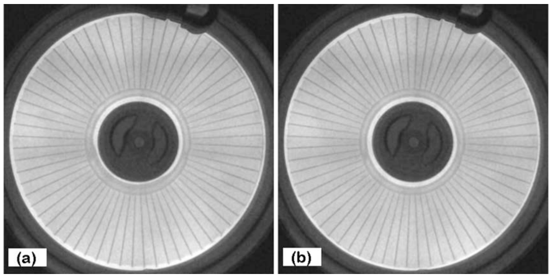

FIG. 12. Photographs showing both sides of an imprinted disk with an inner diameter of 20 mm and an outer diameter of 65 mm.

disk patterning capability and throughput of 180 disks/h. Patterned media applications typically require a modest level of alignment (tens of microns) to ensure that the patterns are concentric to the spindle axis of the disk drive unit; the Imprio HD2200 provides alignment of the template pattern to the disk substrate within 10 μm. An example of a double-sided disk imprint is shown in Fig. 12. The disk shown has an inner diameter of 20 mm and an outer diameter of 65 mm; the patterned area covers the surface in the radial span of 13.5–30.5 mm. The example shown was imprinted using a test template with DTR line/space patterns at a track pitch of 300 nm, with corresponding servo patterns.

D. Quality of imprinted pattern

Feature quality is critical for both DTR and BPM, and preliminary measurements have been performed to characterize each pattern. SEM images were acquired with a JEOL JSM-6340F field-emission SEM at 4 kV and a working distance of ~8 mm. A thin layer (~2 nm) of AuPd alloy was sputtered on the samples prior to microscopy. SEM image analysis was performed using SIMAGIS software provided by Smart Imaging Technologies (Houston, TX). Image processing analysis included normalization of image brightness and removal of angular tilt from line/space images, followed by a threshold function to locate feature edges. Typical analyses are shown in Fig. 13 with corresponding results in Tables I and II. For the BPM example, data were collected across an array of 679 imprinted bits over a total area of 2.12 μm^2. The feature pitch is measured to be 50.0 nm along the track axis, with a 48.8 nm distance between track axes. This array corresponds to a recording density of 0.25 Tbit/in.^{2}. Mean values of feature height (along track axis) and width were measured to be 35.7 and 36.3 nm, respectively, with a standard deviation of about 2 nm. As an example of DTR patterning, Fig. 13(b) shows imprinted lines with a design pitch

TABLE I. Image analysis measurements for BPM pattern in Fig. 13(a).

Measurement	Mean	Standard deviation
Interaxis distance, nm	48.8	0.8
Spot pitch along axis, nm	50.0	1.4
Spot width, nm	36.3	2.2
Spot height, nm	35.7	2.1

TABLE II. Image analysis measurements for DTR pattern in Fig. 13(b).

Measurement	Mean	Standard deviation
Linewidth, nm	43.5	2.1
Line pitch, nm	69.7	3.0
Linewidth roughness $\langle 3\sigma \rangle$, nm	3.0	0.5

of 70 nm. The mean linewidth of the 15 measured lines was 43.5 nm, with a standard deviation of 2.1 nm; linewidth roughness was about 3 nm (Table II). The pattern quality typified by these examples is acceptable in the current phase of technology research, but significant improvements in both resolution and dimensional uniformity will be required to achieve robust data storage densities of 1 Tbit/in.^{2} and above.

IV. CONCLUSIONS

The ever-increasing storage density of hard disk drives is approaching an apparent limitation imposed by the superparamagnetic effect. The practical limitations of superparamagnetism can be avoided by patterning the magnetic domains, but this patterning requires industrial-scale

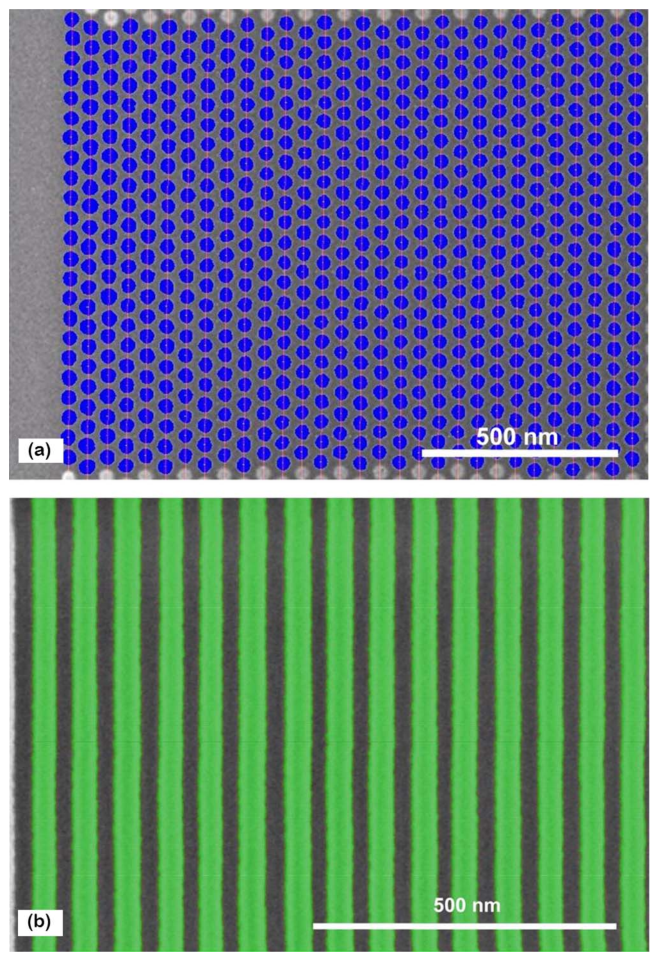

FIG. 13. (Color online) SEM image analysis for (a) 50 nm pitch BPM and (b) 70 nm pitch DTR patterns.

lithography at unprecedented levels of feature resolution, pattern precision, and cost efficiency. S-FIL has demonstrated the potential to fulfill these requirements. Rotating-stage electron-beam lithography tools have been developed to create large-area concentric patterns; ongoing tool development efforts address the stability of these tools for creating highly uniform features during continuous patterning processes that last several days. The master template thus patterned is replicated via imprinting to supply the working templates that are used to pattern hard disk substrates in high-volume manufacturing. The Imprio HD2200 tool has been developed to meet the requirements of two-sided disk imprinting at a rate of 180 disks/h. Further improvements in template mastering and replication processes, together with imprinting tools with increased throughput, are expected to facilitate fabrication of patterned media for the next generation of hard disk drives with storage density exceeding $1\ \mathrm{Tbit/in.}^2$.

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